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Gostner, W.; Schleiss, Anton; Annable, W. K.; Paternolli, M.

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Gravel bar inundation frequency: an indicator for the ecological potential of a river

W. Gostner & A. J. Schleiss
Laboratory of Hydraulic Constructions, Ecole Polytechnique Fédérale de Lausanne, Switzerland

W. K. Annable
Department of Civil & Environmental Engineering, University of Waterloo, Waterloo, Ontario, Canada

M. Paternolli
Patscheider & Partner Consulting Engineers Ltd., Bozen, South Tyrol, Italy

ABSTRACT: In braiding river systems, gravel bars fulfill important ecological functions. At the River Sense, one of the last unregulated rivers in Switzerland, the frequency of gravel bar inundation of a 2 km long site maintaining indicator species such as *Myricaria Germanica* (German Tamarisk) and *Chorthippus pullus* (Gravel Grashopper) was studied. Based upon both detailed data collected in the field and a hydrological analysis of the site, a numerical two-dimensional model of the site was developed to investigate the inundation area and frequency of the parafluvial zone for a range in flow regimes. Results show that the free surface of the parafluvial zone is reduced significantly only when floods with a return period greater than one year occur. Three types of gravel bars were distinguished: gravel bars devoid of vegetation occur for return periods less than two years. The elevation of gravel bars that support *Myricaria Germanica* and *Chorthippus pullus* are at higher discharge elevations that coincide with discharge return frequencies between 2 to 5 years. Densely vegetated overstory and understory communities occur at floods greater than the bankfull return period of five years which also coincide with the floods principally responsible for altering the riverscape. Findings correlate well with the hypothesis that the sustainability of *Myricaria Germanica* and *Chorthippus pullus* is largely dependent upon a specific frequency and duration of intermittent flood inundations.

Keywords: Ecological Potential, Numerical Models, Gravel Bars, Flood Frequency, Inundation

1 INTRODUCTION

Riparian corridors are a nexus between biotic and abiotic environments which change spatially and temporally due to fluvial processes driven by hydrographic events, droughts, water quality, disease, ecological spiraling and dispersion, and anthropogenic influences, amongst many other factors. At the reach scale, the physical riverscape is mostly defined by erosion and depositional processes during flood events when sediment transport capacity and particle entrainment are high. During such discharge events, depositional features (such as point bars and central bars) and floodplains are inundated and their frequency and duration of inundation are directly linked to the intensity and duration of precipitation and snowmelt events.

Tockner and Stanford (2002) have identified floodplain riparian zones as some of the most geomorphologically active and endangered landscapes in the world. Terrestrial vegetation along river banks is frequently eroded and incorporated into flood events resulting in woody debris deposits with receding flows. Correspondingly, the colonization success of successional species which populate point bars, central bars and other mid-channel depositional features between large hydrographic events are also directly coupled to the frequency and duration of hydrographic events. However, the frequency and duration of hydrographic events defining river form may not be commensurate with those which sustain terrestrial growth and colonization. A feedback mechanism may also occur whereby mature terrestrial vegetation can increase the tensile shear strength of bank material leading to reduced rates of bank erosion (Wolman and Gerson, 1978; Thorne, 1990; Knighton, 1998) thus changing the frequency and duration of events where fluvial processes change the riverscape.

In the 21st century, considerable emphasis is being placed on the restoration of riparian corridors as an essential means to enhance the dynamic stability of rivers while correspondingly improving habitat diversity and variability and lowering long-term maintenance expenditures (EU WFD, 2000; FISRWG, 1998). Riparian corridor restoration may involve the removal of river training measures to allow fluvial processes to become re-established within riparian corridors, the physical restoration of channel morphologies through construction measures, removal of levees, bioengineering, terrestrial grooming and enhanced planting, and the protection and preservation of wild areas.

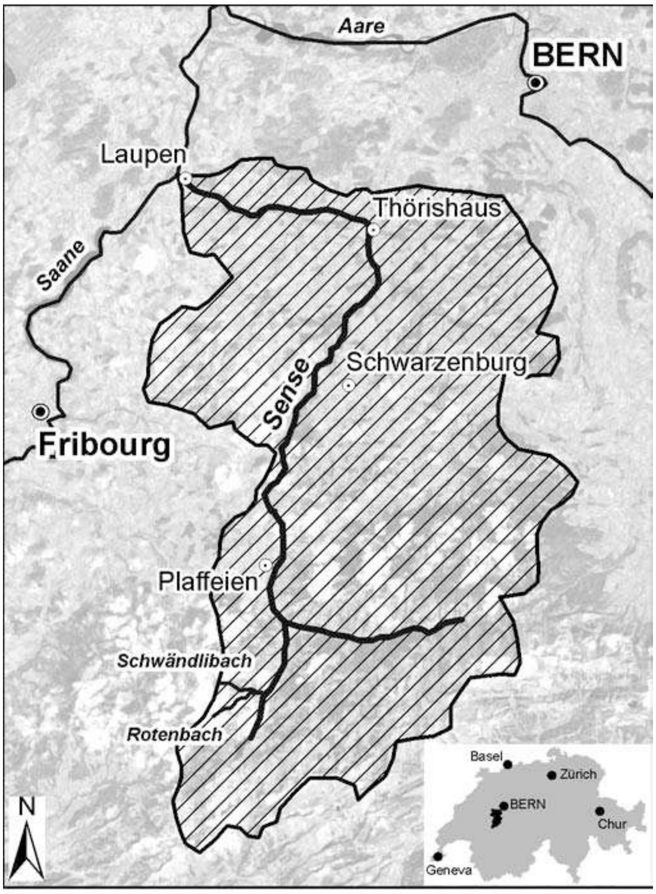
In many countries, there is an added level of complexity in riparian corridor restoration resulting from hydropower schemes which require controlled artificial flood durations and events to produce hydro-electricity. In many cases, the power scheme events can be altered to assist riparian corridor restoration. However, little is currently known about the frequency and duration of inundation of floodplains and mid-channel depositional features and the resulting success of terrestrial species. The aim of this study is to investigate the frequency and duration of flows in a braided river reach where native successional species are known to exist under relatively natural (unregulated) flow conditions. The information arising from this study can then provide power scheme design information on how to best regulate anthropogenic flow regimes to improve and enhance downstream riparian corridors.

2 THE RIVER SENSE

The River Sense is a fourth order watercourse in a 432 km^2 watershed situated in the cantons of Fribourg and Bern, Switzerland (Figure 1). The watershed is one of the last unregulated rivers in Switzerland where hydrographic events are driven by snowmelt and precipitation events without any power schemes or major flow diversion works. Downstream from the confluence of several headwater streams (near Plaffeien – Figure 1), the main stem of the river flows for 35 km before confluencing with the River Saane.

A braided river channel exists in a glacial trough valley near Plaffeien below the mountain headwaters where the sediment transport capacity is high. As the river progresses downstream, the channel enters into a single-thread incised limestone bedrock gorge and then progresses into a single-thread riffle-pool dominated channel morphology. Prior to confluencing with the River Saane, the River Sense is a single-thread plane-bed channel morphology (Montgomery and Buffington, 1997) that has undergone river training over the past several decades.

In the braided parafluvial zones of the river, the morphology is dominated by frequent channel avulsions, mid channel and side channel bars resulting in a highly diverse habitat environment (Lorang and Hauer, 2006) with frequent bank retreats, tree losses, woody debris, emergent vegetation and successional terrestrial species. The return frequency of inundation varies widely between mid and side channel bars, floodplains and terraces. Conversely in the single-thread orthofluvial zones (in particular where river training works have been employed), point bars and side channel bars are inundated much more frequently than the untrained braided reaches.



Watershed of the river Sense

Figure 1. River Sense site location map.

Within the riparian corridor of the River Sense, *Chorthippus pullus* and *Myricaria Germanica* are frequently observed in mid channel and side channel bars which are indicators of high biotic integrity. These species are particularly abundant in the braided reaches where it is expected that the more heterogeneous fluvial environment supports a more diverse aquatic and terrestrial environment (Stanford et al., 2005). Further, the braided channel reaches have highly varied elevations of mid and side channel bars, floodplains and terraces resulting in disparate inundation frequencies allowing several terrestrial species to become established.

In the single thread reaches, there is an observed absence or reduction in *Myricaria Germanica* and *Chorthippus pullus*. The reduction is believed to result from the increased frequency in inundation of the depositional features at similar elevations limiting rooting establishment and hindering the terrestrial community development. On the other hand, floodplain abandonment resulting from reduced upstream sediment supply or headcutting may contribute to the pervasiveness of terrestrial species by changing the frequency of inundation and proximity to the water table. Completely abandoned floodplains are inundated on a less frequent basis and have a reduced susceptibility to erosion which may then contribute less to the destruction of more aggressive species and colonization of more biologically diverse indigenous species.

3 METHODS AND ANALYSIS

3.1 *Study site*

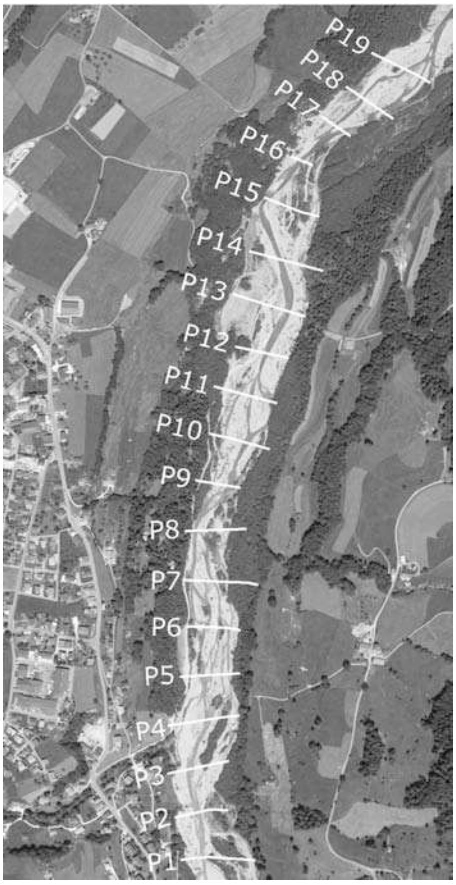


Figure 2. Study site and cross section locations.

The inundation frequency of a braided reach near Plaffeien (Figure 1) is investigated to determine the frequency and duration of discharge events which are considered biologically optimal for the colonization of *Chorthippus pullus* and *Myricaria Germanica*. *Chorthippus pullus* and *Myricaria Germanica* are found in the study reach, however, there are a series of mid channel bars also devoid of the species of interest. Other gravel bars at higher elevations are densely vegetated islands with tree heights approaching 15 meters and absence of *Myricaria Germanica*.

The study site is approximately 2 km in length (Figure 2) with an average bankfull width of 150 m and an effective catchment area of 118 km^2. The area of study is approximately 25 hectares.

3.2 *Field data collection*

Nineteen cross sections and a longitudinal thalweg profile of the channel were surveyed using a first-order differential GPS. Transects were spaced at approximate 100m even intervals perpendicular to the mean channel flow direction to characterize the geomorphic features which included: the channel thalweg, top and bottom of channel banks, bankfull stage, terrace elevations and any additional visual breaks in cross sectional slope. The limits of islands and depositional features were surveyed in addition to the maximum elevation of each feature and the location of woody debris piles.

Substrate size and distribution were characterized using the Wolman pebble count method (Wolman, 1954) at each cross section within the bankfull limits of the channel. Grain size distribution plots were generated for each cross section and the median particle diameters of log-normal distribution plots used to determine the median grain size diameter (D_{50}) as illustrated in Figure 3. The median reach particle diameter was found to be 53 mm which relates to a very coarse gravel substrate.

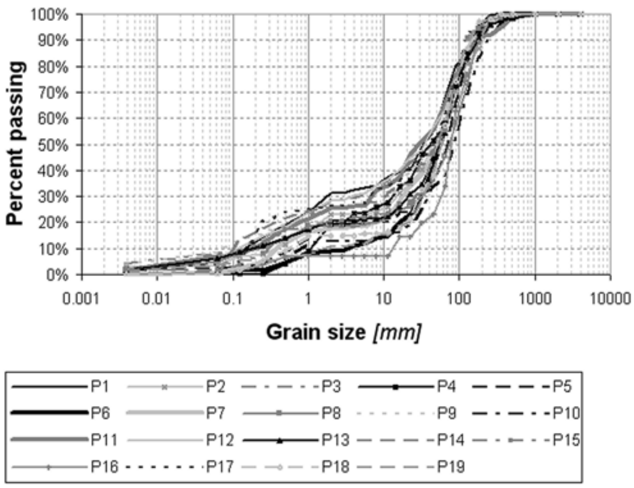


Figure 3. Grain size distribution curves at each transect

Hydraulic roughness (k_s) was estimated from the results of the Woman Pebble count using the Strickler equation of the form (Strickler, 1923):

$$k_s = \frac{21.1}{D_{50}^{1/6}} = \frac{1}{n} \quad (1)$$

where n is the Manning's roughness coefficient. An average value of $k_s = 34m^{1/3}s^{-1}$ was obtained for the entire study reach. An average reach roughness coefficient was used rather than discrete values obtained at each cross section since at discharges approaching mid channel bar inundation, there is significant course grain sediment transport leading to a redistribution in the bed material that cannot be adequately quantified in addition to changes in the wetted perimeter resulting from scour and deposition.

Discharge velocities were obtained within the flowing sections of each cross section using the six-tenths velocity method in addition to velocities being measured 0.05m above the channel bed. Velocities obtained at 0.05m were considered to relate to the nose running depth of fish that would occupy the lotic environments. Discharge velocities were obtained using a Sontek Flow Tracker® acoustic Doppler velocity meter and their specific locations surveyed using a GPS.

The spatial location of the terrestrial species of interest were acquired from a parallel biological inventory using a hand held GPS. Ground elevations at each plant location were related to ground elevations obtained in the first order differential transect surveys.

3.3 *Hydrology*

A hydrometric monitoring gauge station was not available at the study site proper. However, two gauge stations are located upstream (approximately 7 km) located on two tributaries at Rotenbach and Schwändlibach, one gauge located 15 km downstream at Thörishaus and a fourth gauge on the River Saane at Laupen immediately downstream of the confluence with the River Sense (Figure 1). Flow duration curves were developed for each of the four gauge stations and a watershed scaled flow duration curve developed for the study site (Figure 4) using the Swiss regionalized model developed by Pfaundler & Zappa (2006) which is based upon ordinal datasets between 1981 and 2000. The model assumes there is a contiguous logarithmic function between watershed area and discharge.

At the Thörishaus gauge station 15 km downstream, the mean annual discharge was calculated to be 8.7 m^3/s and using a logarithmic discharge scaling factor of 0.66 for the study site at Plaffeien, a mean annual discharge was estimated as 4.2 m^3/s. Validation of the scaling factor was achieved using the calculated discharge from velocity measurements during field inventories and compared to those of the Thörishaus gauge station during the same days of observation. On the day of field measurement, the average daily discharge at Thörishaus was 4.8 m^3/s. Using the logarithmic model, a predicted discharge at Plaffeien was 2.8 m^3/s whereas a field measured discharge of 2.3 m^3/s was calculated. It is important to note that on the day of flow measurement, discharge varied slightly during the day of measurement between cross sections. The average discharge from all 19 cross section velocity measurements and discharge calculations were used. Given the small error between the observed average daily discharge and that predicted using the logarithmic model, we assume that the flow duration curve developed at the Thörishaus gauge could be extrapolated with reasonable certainty to the study site.

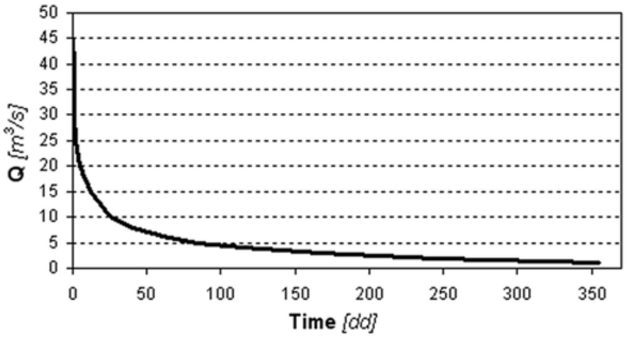


Figure 4. Study site flow duration curve.

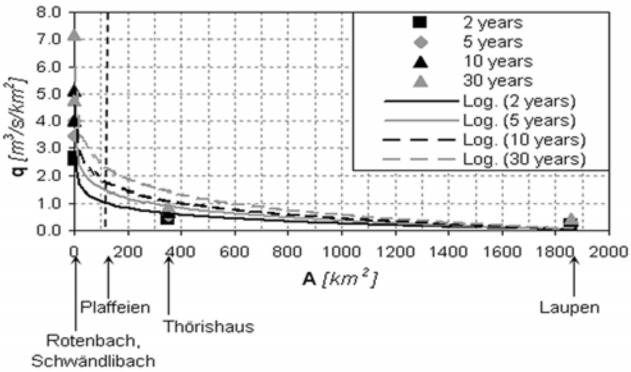


Figure 5. Interpolation of specific discharges between the available gauges by means of a logarithmic law

Table 1. Return frequencies and extrapolated discharges.

Return period	Q
years	*m³/s*
2	124
5	172
10	208
30	266
50	296

Flow frequency analysis using the Log Pearson III analysis method were conducted for a series of return periods between 2 to 50 years for the four gauge stations over each period of record. The return periods were extrapolated for the Plaffeien study site using the same logarithmic scaling factor (Figure 5). Table 1 lists the return periods and associated flows extrapolated for the Plaffeien site.

3.4 *Numerical model development*

The numerical model FLUMEN (FLUvial Modelling ENgine) was used to investigate the spatial distribution and inundation frequency of depositional features of the study site. FLUMEN is a two-dimensional surface water model which can be used to investigate hydraulic behavior of rivers and coastal waters in a myriad of discharge conditions. The solution method is solved using depth-averaged shallow water flow equations on a cell-centered unstructured mesh that allows for wet and dry domains, sub- and supercritical flow conditions, and the specification of variable bed topography (Beffa, 2004).

In the current study, the river bed was assumed to be stable. We recognize that a static river bed is an over-simplification of the braided river reach of study, however, the modeling domain cannot accommodate a dynamically changing grid configuration which would be consistent with a braided river reach under various high flow conditions. Nevertheless, for an initial investigation in determining the frequency and duration of depositional features and how these temporal metrics relate to terrestrial colonization, the proposed model should provide sufficient accuracy.

Nineteen cross sections, additional survey points, and surrounding upland data extracted from digital terrain were used to define the modeling domain of the River Sense at Plaffeien which is illustrated in Figure 2. An average Manning's roughness value of 0.03 was used for the bankfull channel (Equation 1) using the results of the pebble count analysis. Flood plain roughness beyond the limits of the bankfull channel and mature tree stands on islands were estimated in the range of $0.05 < n \leq 0.10$ and associated with the density and calliper of vegetative communities as suggested by Chow (1959).

3.5 *Calibration of model*

Model calibration was conducted using field measured velocities and the calculated discharge for the observed flow condition of 2.4 m^3/s where measured versus estimated flow depths were compared.) Further, flow depths were only compared at cross sections where the total flow occurred in a single channel, rather than multiple flow paths. The single flow path sites were selected as they offered greater flow depths and decreased cross sectional variability leading to better comparison between observed and predicted flow depths. The most upstream and downstream cross sections were also eliminated from the comparison arising from boundary condition limitations in the numerical model.

Figure 6 shows the geodetic elevations of the thalweg profile (bed elevation) and of the calculated and measured water level along a segment of the modeled reach. Simulated average flow depths, calculated as difference between thalweg and water level elevation, correlate very well with field observations.

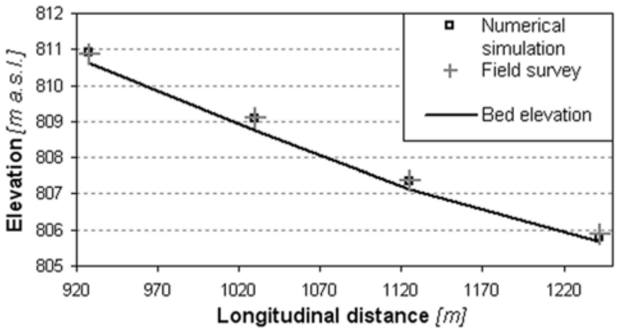


Figure 6. Comparison between measured and predicted water elevations for 4.3m^3/s.

The bankfull discharge frequency was also calculated as a qualitative metric to evaluate the accuracy of the model to the flow regime commensurate with initial flooding of the floodplain regions. Kellerhals et al. (1972) observed that the return frequency of bankfull discharge in braided rivers of western Canada ranged between 2 years and 7 years. Williams (1978) studying both braided and single thread channels observed bankfull return frequencies ranging between 1.1years and 25 years but did not stratify his data into specific channel morphologies. A series of simulations were conducted with varying discharges to determine what discharge (and associated return period) correlated best with the field observed bankfull discharge and associated depth along the longitudinal profile of the channel. A discharge of 172 m^3/s (relating to a 5-year return period) best correlated with observed flow depth conditions (Figure 7). The return period coincides with the range of previously observed discharge return periods in other braided river systems which provides additional confidence in the predictability of the model.

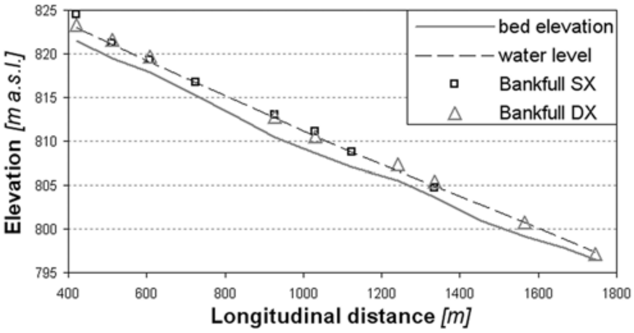


Figure 7. Comparison between bankfull height and water level for 172 m^3/s.

4 RESULTS

4.1 *Overall study site*

Six inundation simulations were conducted between low flow conditions and the 10-year discharge ranging between 2 m³/s and 220 m³/s. The spatial distribution of inundation of the study reach is illustrated in Figure 8. The results illustrate that with increasing discharge, an increasing proportion of the river bed is inundated which increases the number of isolated regions (pseudo islands) up to a flow of approximately 57 m3/s (which relates to a 0.5 year discharge return frequency) followed by a decrease in isolated regions until the majority of the channel is inundated at 200 m3/s. The remaining dry regions correlate with islands identified from field investigations were mature and well established tree stands exist.

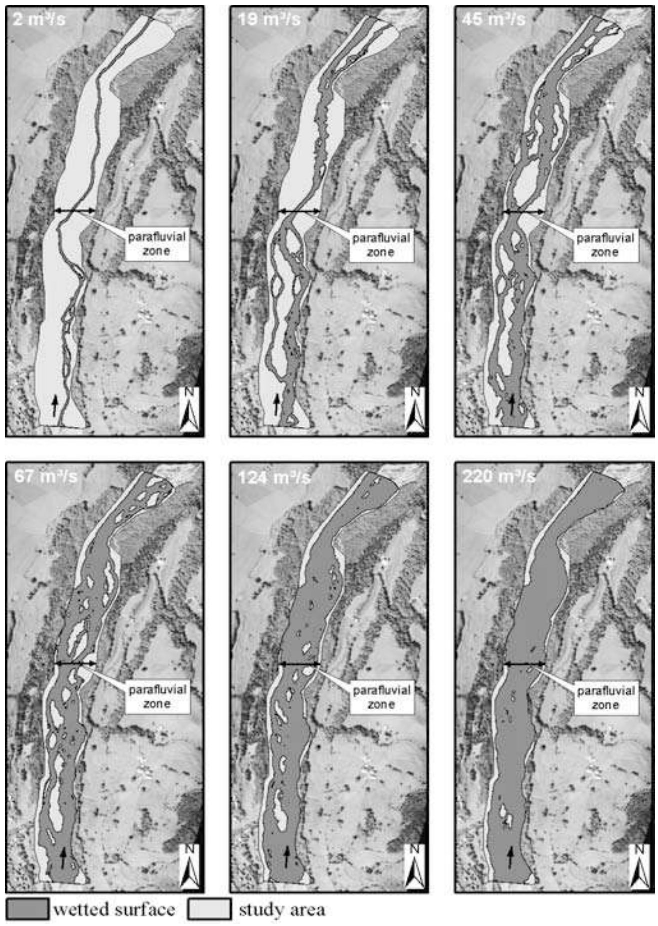


Figure 8. Parafluvial zone inundation with varying flow regimes.

Based upon the two-dimensional hydraulic analysis, a relationship was derived between the exposed (dry) surface area of the study reach and the annual duration of exposure (Figure 9). The relationship shows that at base flow conditions (2m ^{3}/s), 20000 m^2 of the parafluvial zone is inundated and that the inundation trend follows a logarithmic profile with decreasing annual duration (increasing discharge). At the annual average maximum discharge, approximately 140000 m^2 of the study reach is inundated which relates to 56 % of the total parafluvial zone. Further, for over half of a year in an average discharge year, only 10% of the total parafluvial zone is inundated while 20% of the parafluvial zone is inundated for 25 days/year or less.

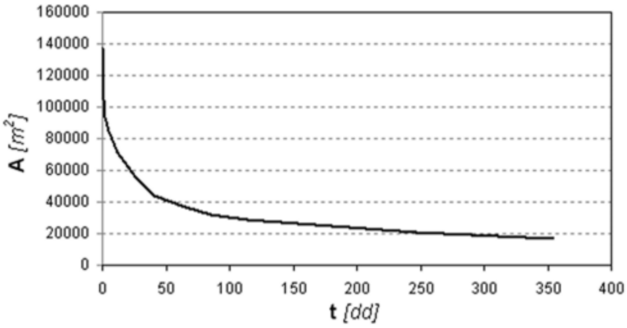


Figure 9. Wetted parafluvial zone area versus annual duration.

Relative percentages of inundated (wet) and exposed (dry) parafluvial zones were calculated for a series of discharge simulations related to specific frequency return periods and a relationship developed between relative area wet/dry percentages and discharge return frequency (Figure 10). A rapid increase in inundation area occurs within the parafluvial zone up to approximately the 2-year return period (approximately 85% wetted surface area). With increasing discharge return frequencies the relative areal increase in inundation significantly decreases. The rapid increase in parafluvial zone inundation relates to the range in discharges that are filling the bankfull channel in which all of the mid-channel and side channel bars exists. Beyond the two-year return period, only the highest elevation island remain above the water surface and correlate with the locations of well established island vegetative communities. A small percentage of the parafluvial zone remains above the water table at the 30-year return period, these elevations relate to an abandoned terrace elevation that has persisted over several decades.

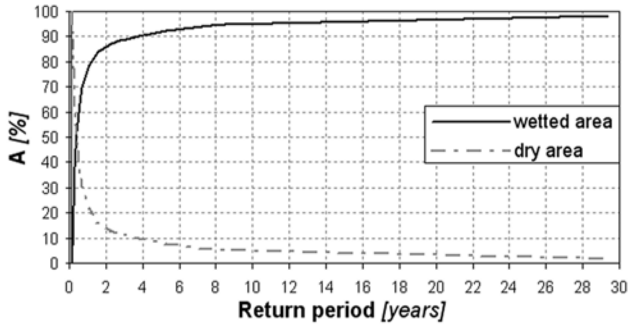


Figure 10. Trend of wetted and dry area in the entire floodplain for floods with different return period.

4.2 *Special area of interest*

A particular sub-reach of the study area was evaluated in closer detail between cross sections 3 and 9 (Figure 2). The sub-reach is of particular interest as the area has several gravel bar deposits of varying elevations where some bars support *Myricaria Germanica* and *Chorthippus pullus*, some support tree stands and some have an absence of either. The surface area of the parafluvial zone is 39040 m^2 and has a longitudinal distance of 600m and an average bankfull with of 130 m.

Rather than evaluating areal percentage of parafluvial inundation as it relates to pre-determined discharge frequency, here we determined the discharge related to the water surface elevation when the elevation of specific gravel bars and island became inundated. A relationship could therefore be developed between exposed (dry) percent parafluvial zone and discharge at vertical stages or "thresholds" when inundation significantly changes. The discharge thresholds were determined by evaluating a series of simulations and identifying inflection points in the relationship between the change in exposed parafluvial area (dA) and change in discharge (dQ) as a function of discharge. Evaluating local maxima or minima in the rate of change of dA/dQ identifies the threshold discharges where significant changes in exposed surface area (relating to the inundation of gravel bars) occur. The objective of this analysis was to correlate particular discharges and their return frequencies to the success in migration of *Chorthippus pullus* and colonization of *Myricaria Germanica* at certain gravel bar sites.

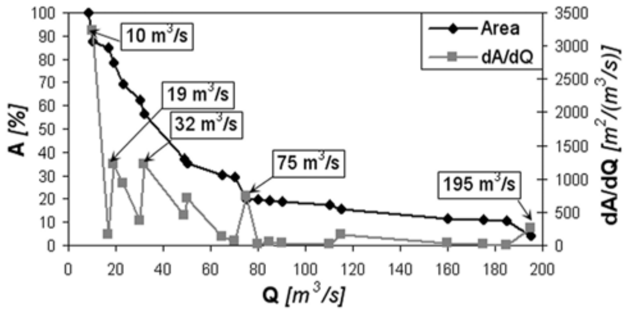


Figure 11. Decreasing of gravel bar continuous dry area due to the growth of discharge.

Figure 11 identifies the thresholds values in dA/dQ as a function of discharge over a broad range in simulated discharge values and return frequencies. Seven threshold discharges were identified: 10, 19, 32, 75, and 195 m^3/s which then relate to water surface elevations where there are significant changes in parafluvial inundation. Figure 12 illustrates the spatial distribution of dry and wet zones for the sub-study reach. It is noted that an additional base case of 8.5 m^3/s is also illustrated: which is the lowest discharge when two flowing channels begin to form in the parafluvial zone. The dashed regions in Figure 12 depict the dry surfaces in the area of interest, while the darker solid shading identifies the inundated regions.

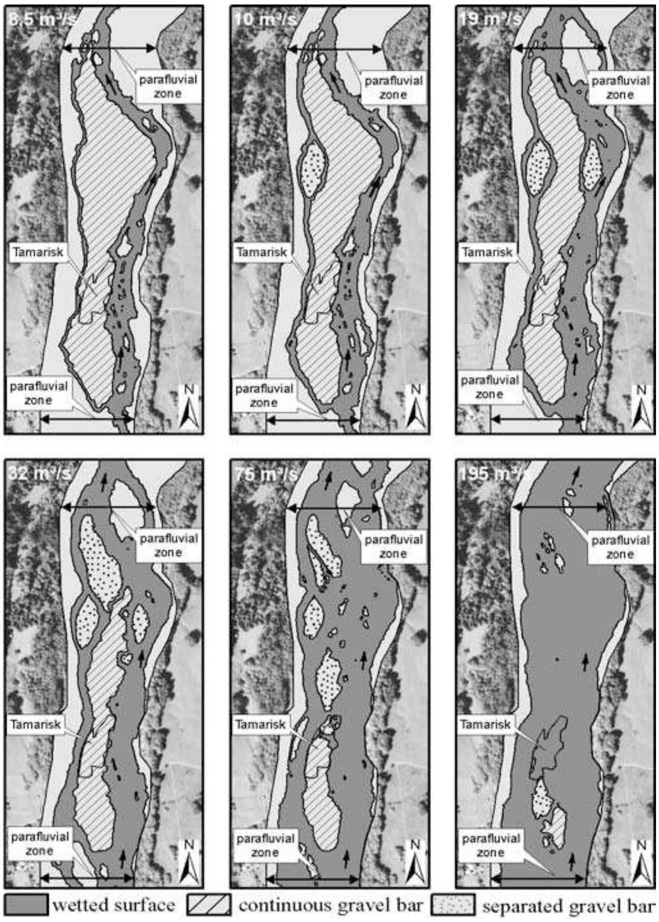


Figure 12. Wetted and dry areas with changing discharges.

As illustrated in Figure 12, at a discharge of 10 m^3/s a new flow path emerges on the left hand side of the channel forming an island. By 19 m^3/s, an additional bifurcation in flow occurs on the right hand side of the channel leading to an additional island. The formation of branches that evulse the principle dry zone from left to right occur between discharges of 32 m^3/s and 75 m^3/s. A discharge of 75 m^3/s relates to a return period of around 1.3 years. At the flow stage related to 75 m^3/s, the majority of the gravel bars devoid of vegetation are submerged, while the bars with *Myricaria Germanica* are still above the water surface. In the discharge range between the 4 and 5 year return frequency (just below bankfull discharge), areas populated by *Myricaria Germanica* are completely inundated.

Beyond 75 m^3/s, no significant change in inundated surface area occurs until a discharge of 195m^3/s (7-year return period) is achieved which is above the bankfull stage (a discharge of 172 m^3/s and a five-year return period). At a discharge of 195m^3/s the adjacent floodplains will also be inundated and this final inundation elevation relates to a low terrace elevation. The remaining island surface elevation above the water level coincides with the mature tree stand, which has a surface of 1530 m^2 relating to 4 % of the total parafluvial zone. For discharges with return periods greater than 20 years, the entirety of the parafluvial zone is inundated.

5 CONCLUSIONS

A two-dimensional surface water model of a braided river reach of the River Sense in Switzerland was developed to investigate the persistence of terrestrial species with specific habitat requirements. Three dominant types of depositional features exist within the parafluvial zone. Depositional features devoid of vegetation are typically inundated in flows less than a two-year return period. Depositional features where *Chorthippus pullus* and *Myricaria Germanica* persist were found to become inundated at discharge return frequencies ranging between 4 years and 5 years. Depositional features, floodplains and abandoned island terraces where mature overstory and understory tree stands persist were found to be flooded at discharge return frequencies greater than 5 years. All parafluvial features were inundated when discharges exceeded a 20 years return period.

In single thread unregulated gravel-bed river channels, bankfull discharge is often correlated with a 1.5 year – 2 years return period (Leopold et al., 1964) and also maintains a relatively homogeneous wetted perimeter (relative to a braided channel). The absence of *Chorthippus pullus* and *Myricaria Germanica* in single thread channels may be related to the channel morphology or the frequency of orthofluvial inundation.

The results presented here provide initial insights into methods for linking the persistence of terrestrial species of interest with hydrologic and hydraulic tools. With sufficient coupled investigation of biotic and abiotic characteristics in a myriad of channel morphologies under a range in flow regimes, it is expected that flow regulation guidelines can be developed to optimize channel flow for both hydro-electric demands while enhancing terrestrial community restoration.

ACKNOWLEDGMENTS

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